Guide to Durable Concrete

Reported by ACI Committee 201

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This guide describes specific types of concrete deterioration. Each chapter contains a discussion of the mechanisms involved and the recommended requirements for individual components of concrete, quality considerations for concrete mixtures, construction procedures, and influences of the exposure environment, which are all important considerations to ensure concrete durability.

This guide was developed for conventional concrete but is generally applicable to specialty concretes; however, specialty concretes, such as roller-compacted or pervious concrete, may have unique durability-related issues that deserve further attention that are not addressed herein.

Keywords: abrasion resistance; alkali-aggregate reaction; chemical attack; curing; deterioration; durability; freezing and thawing; physical salt attack, sulfate attack.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Concrete is the most widely used construction material in the world. The design, detailing, and execution of concrete to resist weathering action, chemical attack, abrasion, and other processes of deterioration over its intended service life will determine its durability. Durable concrete will retain its original form, quality, and serviceability when exposed to its environment. Properly designed, proportioned, transported, placed, finished, and cured concrete is capable of providing decades of service with little or no maintenance. Yet certain conditions or environments exist that can lead to concrete deterioration. Deterioration mechanisms are either chemical or physical in nature and may originate from within the concrete, or may be the result of the external environmental exposure. Chemical and physical attacking mechanisms often work synergistically. Depending on the nature of the attack, distress may be concentrated in the paste, aggregate, or reinforcing components of the concrete, or a combination thereof.

The various factors influencing durability and a particular mechanism of deterioration should be considered in the context of the environmental exposure of the concrete. In addition, consideration should be given to the microclimate to which the specific structural element is to be exposed. The type and severity of deterioration of a given structure may be affected by its proximity to sources of deleterious agents or agents that facilitate distress, exposure to wind, precipitation, or temperature. For instance, exterior girders in a bridge structure may be exposed to a more aggressive environment than interior girders.

The concept of service life is increasingly used for the design of new structures. To produce concrete suitable for a particular application, required service life, design requirements, and expected exposure environments, both macro and micro, should be determined before defining the necessary materials and mixture proportions.

The use of good materials and proper mixture proportioning will not, by itself, ensure durable concrete. Appropriate placement practices and workmanship are essential to the production of durable concrete. Fresh concrete can be consolidated and molded to the shape desired to serve its intended purpose. During this stage, a number of properties significantly influencing the durability of the hardened concrete are established. Pore structure development, air-void system formation, material uniformity, and potential for cracking are established at early ages and are important to the ultimate durability of concrete. As such, durable concrete requires the application of good quality control during construction. Inspection and testing by trained and certified personnel can help ensure the use of durable mixtures and proper practices.

1.2—Scope

This guide discusses the important mechanisms of concrete deterioration and gives recommendations on how to mitigate or minimize such damage. This guide also addresses durability by first discussing the importance of mass transport and then addressing specific modes of attack in separate chapters. These include freezing and thawing, alkali-aggregate reaction (AAR), sulfate attack, aggressive chemical attack, physical salt attack, corrosion of metals and other embedded materials, abrasion, or a combination of these. Fire resistance of concrete and cracking are not addressed directly. Fire resistance is covered in ACI 216.1 and cracking is covered in ACI 224R and ACI 224.1R. While cracking does impact the durability of concrete in severe exposures, the different causes of cracking and their specific impacts are not discussed. Cracking is only mentioned in general terms regarding its impact on fluid ingress.

CHAPTER 2—DEFINITIONS

2.1—Definitions

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology," https://www.concrete.org/store/productdetail.aspx?ItemID=CT16. Definitions provided herein complement that source.

advective transport—transfer of heat or matter via the bulk motion of a fluid.

alkali loading (or content)—total amount of equivalent alkalis (Na_2O_e) in a concrete mixture expressed as mass per volume.

calcium sulfoaluminate cement—product obtained by pulverizing clinker containing mainly ye′elimite [$Ca_4(AlO_2)_6SO_4$] that is often used in expansive cements and ultra-high-early-strength cements.

diffusion—movement of species, such as ions, gas, or vapor, from an area of higher concentration to an area of lower concentration, independent of the bulk motion of a fluid.

electrical migration—transport of electrons or ions due to an electric potential gradient.

ice lens—layer of ice, generally parallel to the exposed surface of the concrete, that can produce internal damage and also lead to scaling or delamination.

leaching—dissolution and removal of soluble components such as calcium hydroxide from concrete.

permeability—the ability of a given concrete to permit liquids or gases to pass through.

permeation—flow of a liquid, gas, or vapor within a solid under the action of a pressure gradient.

physical salt attack—mechanism in which concrete or mortar is damaged as a result of salt crystallization pressure.

reactive silica—form of silica, often amorphous or crypto-crystalline, that dissolves when in contact with concrete pore solution having a sufficiently high concentration of hydroxyl ions.

salt weathering—form of deterioration most commonly observed in arid climates where exposure to soluble salts and cyclic variations in temperature and relative humidity can lead to salt crystallization.

thaumasite—silicate mineral, colorless to white prismatic hexagonal crystals typically as acicular radiating groups, with the chemical formula $\{[Ca_3Si(OH)_6 \cdot 12(H_2O)](SO_4)(CO_3)\}$.

CHAPTER 3—MASS TRANSPORT

3.1—Introduction

Concrete is a multiphase porous medium consisting of a multiscale porous cement paste matrix with aggregate inclusions. Liquid and gas may be present in any pores and microcracks. As such, it is susceptible to the ingress and movement of substances (fluids or ions) from its environment within and through its pore system. This chapter discusses the transport of gases, liquids, and ions in solution through concrete (Lichtner et al. 1996; Baer 1988; Hearn et al. 2006; Hall and Hoff 2012). Methods for improving the durability of concrete and some of the common test methods used to measure the transport properties, along with their advantages and limitations with regard to assessing concrete durability, are also discussed. It is recognized that the rate of ingress of fluids and ions will increase by the presence of cracks. However, the specific influences of different types of cracks and crack widths are not discussed herein.

The ingress of gases, liquids, or ions in solution through concrete may initiate chemical processes, physical processes, or both, that affect the durability of the concrete under a given set of service conditions. Water itself may be harmful because of its ability to leach calcium hydroxide (CH) from the hardened cement paste and because of osmotic pressures generated as water flows to sites of higher alkalinity (Powers et al. 1954; Powers 1975; Helmuth 1960b,c). In addition, water may also be acidic or carry harmful dissolved chemicals, such as chlorides or sulfates, into the concrete. The ingress of gases such as oxygen and carbon dioxide through the concrete pores can contribute to the corrosion of steel reinforcement.

Different substances may interact with components of the concrete in different ways; therefore, transport of a substance through concrete is unique to that substance. For example, water can hydrate previously unhydrated cement particles or leach calcium. Chloride ions may be bound by the hydration products of cement or supplementary cementitious materials (SCMs). The size of the molecules or ions that are transported through the concrete, viscosity of the fluid, valence of the ions, and other ionic species present also affect the transport properties. Thus, permeability and diffusivity must be expressed in terms of the substance that is migrating through the concrete. In general, concrete with transport properties that limit the rate of ingress of external agents is not immune to chemical deterioration, but the effects are mainly near the exposed surfaces, so the concrete tends to be more durable.